A study of pickup and signal processing for HLS-Ⅱ bunch current measurement system*

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Abstract: For the HLS-Ⅱ bunch current measurement system, in order to obtain the absolute value of bunch current, the calibration factor should be determined by using DCCT. At the HLS storage ring, the stretch effect of bunch length is observed and the change rate is about 19% when the bunch current decays over time and this will affect the performance of bunch current detection. To overcome the bunch stretch influence in the HLS-Ⅱ bunch current measurement, an evaluation about pickup type and signal processing is carried out. Strip-line pickup and button pickup are selectable, and the theoretical analysis and demonstration experiment are performed to find out an acceptable solution for the bunch current measurement system at HLS-Ⅱ. The experimental data analysis shows that the normalized calibration factor will change by about 27% when the bunch length changes by about 19% if using the button pickup and processing by peak value of bunch signal; the influence will be reduced to 2% less if adopting the strip-line pickup and integral.

Key words: bunch current, bunch length, strip-line electrode, button electrode, BPM, DCCT

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1 Introduction

Hefei Light Source (HLS-Ⅱ) is a dedicated second generation VUV light source, and its storage ring operates in 800 MeV with 204.016 MHz RF and 45 bunches. The bunches are separated from each other by only 5 ns, and the bunch length is about 300 ps. Bunch current is an important parameter for studying the injection fill-pattern in the storage ring and the instability threshold of the bunch. In particular, the bunch current monitor is a necessary tool for the top-up injection in an accelerator. A bunch by bunch current measurement (BCM) system [1] has been developed to meet the needs of the upgrade project of HLS-Ⅱ.

Various types of bunch current or bunch charge measurement systems have been developed worldwide. Fast current transformers, electrode-pickups and wall current monitors are the most popular signal pickups for bunch current measurement. Typically, a beam position monitor (BPM) has four electrodes, and the sum signal of the four electrodes carries the bunch charge information and its change rate is less than 0.005 when the beam position is alternated within 4 mm [2]. So the sum signal can be used to calculate the bunch current. At BEPC-Ⅱ and SSRF, button electrode BPMs are selected as signal pickups of bunch current detection [3, 4].

Two types of four-electrode pickup can be selected as the pickup for HLS-Ⅱ bunch current measurement system: button electrode and strip-line electrode. The peak value or integral of bunch signal from the pickup can be used to calculate the related bunch current value. To obtain the absolute value of bunch current, the calibration factor should be determined by using DC current transformer (DCCT). At HLS, the stretch effect of bunch length was observed [5] when the bunch current decayed over time, and this will affect the performance of bunch current detection for different pickups and calculation methods, which have not been taken into consideration in other accelerators. So, to find out an ideal solution for the bunch current measurement at HLS-Ⅱ, the evaluation about pickup type and signal processing is presented in this paper.

2 The signal pickup and calculation technique

Button electrode and strip-line electrode pickups are

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candidate signal pickups for the HLS-Ⅱ bunch current measurement. To overcome the bunch stretch influence on the bunch current detection, it is necessary to understand the pickup sum signal and to find the effective signal processing technique.

The electrons in a bunch in an electron storage ring are usually expressed with a Gaussian distribution [1]. When the total charge in a bunch is Q_0 and the bunch length is σ_τ, Eq. (1) shows the expression of a bunch in time domain.

$$I_{\rm b}(t)=\frac{Q_0}{\sqrt{2\pi}\sigma_\tau}\exp\left(-\frac{t^2}{2\sigma_\tau^2}\right). \tag{1}$$

For the button type pickup, the sum signal of four electrodes can be expressed as Eq. (2):

$$V_{\rm b\_\Sigma}(t)=-k\frac{{\rm d}I_{\rm b}(t)}{{\rm d}t}=k\frac{Q_0}{\sqrt{2\pi}\sigma_\tau^2}t\exp\left(-\frac{t^2}{2\sigma_\tau^2}\right). \tag{2}$$

k is the scale factor of electronics. The chart is shown in Fig. 1(a). The peak value or integral value of each bunch sum signal carries bunch charge information, which can be obtained from Eq. (2):

$$V_{\rm b\_peak}=K_{\rm p}\frac{Q_0}{\sigma_\tau^2}\propto\frac{Q_0}{\sigma_\tau^2}, \tag{3}$$

$$V_{\rm b\_integral}=\int_{t1}^{0}V_\sigma(t){\rm d}t=K_{\rm I}\frac{Q_0}{\sigma_\tau}\propto\frac{Q_0}{\sigma_\tau}, \tag{4}$$

where $K_{\rm p}$ is the calibration factor for using the peak value of sum signal and $K_{\rm p}$ is the calibration factor for using the integral of sum signal. The above equation shows the influence of the bunch length σ_τ, both on $V_{\rm b\_peak}$ and $V_{\rm b\_integral}$.

Similarly, for the strip-line electrode, the sum signal can be expressed as Eq. (5) and the chart is shown in Fig. 1(b):

$$V_{\rm s\_\Sigma}(t)=-\frac{\varphi Z}{4\pi}\left[I_{\rm b}(t)-I_{\rm b}\left(t-\frac{2l}{c}\right)\right]. \tag{5}$$

From Eq. (5), $V_{\rm peak}$ and $V_{\rm integral}$ are approximated as follows:

$$V_{\rm s\_peak}=K_{\rm p}\frac{Q_0}{\sigma_\tau}\propto\frac{Q_0}{\sigma_\tau}. \tag{6}$$

$$V_{\rm s\_integral}=\int_{t1}^{t2}V_\sigma(t){\rm d}t=K_{\rm I}Q_0\propto Q_0. \tag{7}$$

Eq. (6) shows that the peak value of sum signal of strip-line electrodes $V_{\rm s\_peak}$ is in proportion to the bunch length σ_τ and at the same time is in inverse proportion to Q_0. However, Eq. (7) shows that the integral value $V_{\rm s\_integral}$ is proportional to bunch charge Q_0 and has no influence on the bunch length σ_τ.

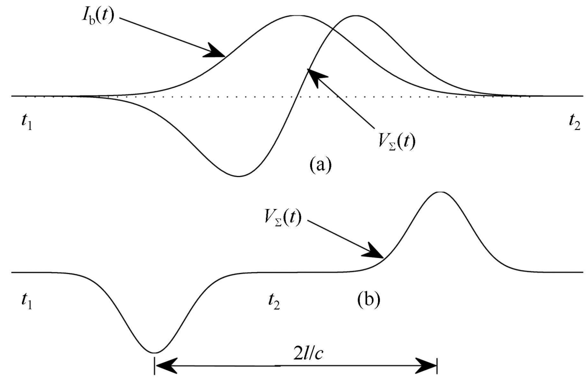

Fig. 1. The expression of a bunch in time domain and sum signal from BPM. (a) sum signal from button electrodes; (b) sum signal from strip-line electrodes.

3 Experimental data analysis

To evaluate and verify how the bunch length influences the calibration factor of bunch current measurement in different pickup types, the beam current (by DCCT), bunch length (by streak camera) and the bunch current are monitored at the same time in the HLS electron storage ring. The data acquisition unit for bunch current measurement is a digital oscilloscope (Agilent MSO7104). An 800 MHz low pass filter is used to reduce the leak of frequency spectrum for the limited bandwidth of the digital oscilloscope.

3.1 Bunch length stretch effect at HLS

Figure 2 shows the DCCT beam current value decays over time. The beam current decays from 200 mA to 80 mA within about 10 h when the HLS storage ring is in 800 MeV energy and 45 bunches operation mode.

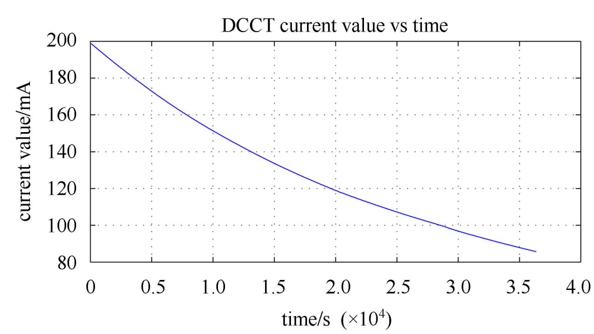

Fig. 2. The DCCT beam current value.

At the same time, the bunch length can be obtained from the streak camera. With the beam current decay [5], the stretch effect of bunch length is observed. Fig. 3 shows that the bunch length (averaged) changes from 303 ps to 244 ps with the beam current decay and the change rate is about 19%.

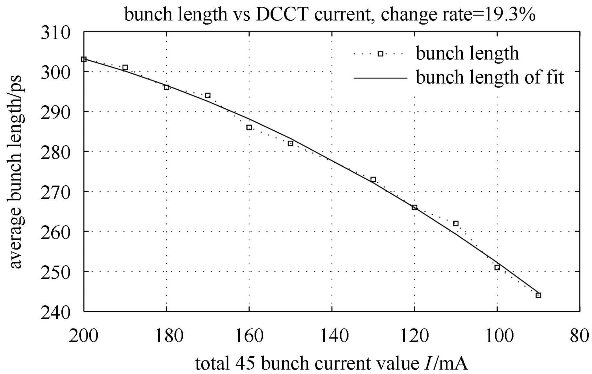

Fig. 3. Bunch length changed with bunch current.

3.2 Bunch signal processing

The RF of HLS is 204 MHz, so the bunch spacing is about 5 ns, and the width of bunch pulse after the extension by signal transmission network is about 300 ps. The above parameters are the same in HLS-Ⅱ. The sampling rate of the oscilloscope is 2 GHz per channel and is not enough to obtain the integrated value or peak value of every bunch in one revolution time. The way to solve this problem is by software. At HLS electron storage ring the lifetime of a beam is about 7 hours. For bunch current detection, bunch current decay can be omitted in hundred turns. A waveform-reconstruction algorithm, that is, equivalent sampling, is used to improve time resolution [6]. The idea of this algorithm is that of mapping sample values of each circle to the corresponding time of the first circle with a sorting algorithm, making use of the relationship that radio frequency is not in direct portion to sampling rate.

For HLS bunch current measurement system, fifty turns signal was recorded in every processing period and were rebuilt to one turn signal, and an effective sampling rate of about 100 GHz was obtained.

Sum signal from button and strip-line pickup have been recorded by the digital oscilloscope in two sampling channels at the same time. Fig. 4 shows the rebuilt waveform of sum signal from four-strip-line pickup, including all 45 bunches.

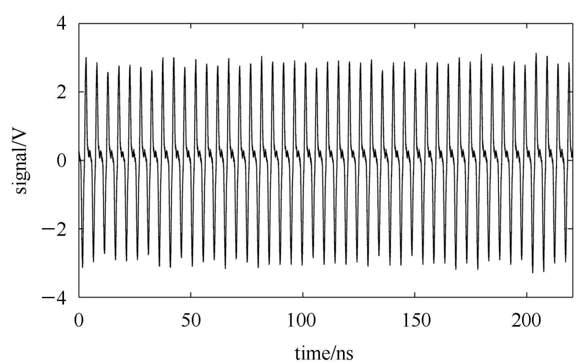

Fig. 4. The sum signal of four-strip-line pickup with 45 bunches.

Figure 5 shows waveform of one bunch from strip-line type pickup and Fig. 6 shows waveform from button type pickup. Each bunch shape can be restored very well.

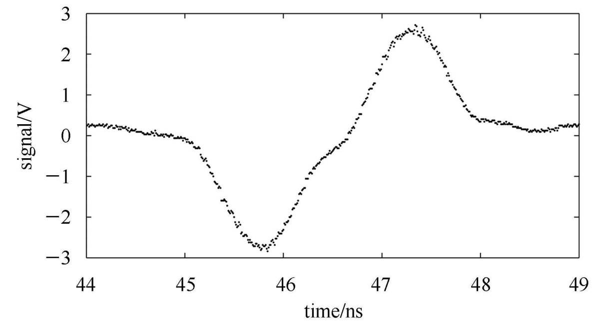

Fig. 5. The sum signal of four-strip-line pickup with one bunch.

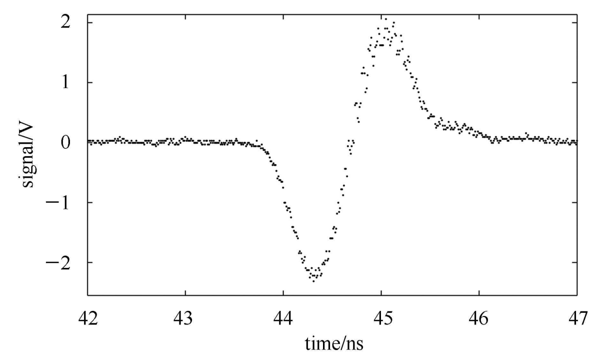

Fig. 6. The sum signal of four-button pickup with one bunch.

3.3 Calibration factor for bunch current

The amplitude of each bunch called the relative bunch current from the sum signal of BPM is calibrated, and normalized to get the absolute value of each bunch current. In the case of ignoring the difference of the calibration coefficient for each bunch current, each bunch current is calculated as follows:

$$I_i = KA_i, \quad i=1,2,3,\cdots,N, \tag{8}$$

where A_i is the peak value or the integral value of the sum signal of BPM, K is the calibration factor, N is the number of bunches. The calibration factor can be calculated with Eq. (9)

$$K=\frac{I_{\rm dcct}}{\sum\limits_{i=1}^{N} A_i}, \quad i=1,2,3,\cdots,N, \tag{9}$$

where $I_{\rm dcct}$ is the DC beam current obtained from the DCCT system.

With the beam current decay from 200 mA to 80 mA, we can calculate the calibration factor which changes following the beam current. The normalized calculation

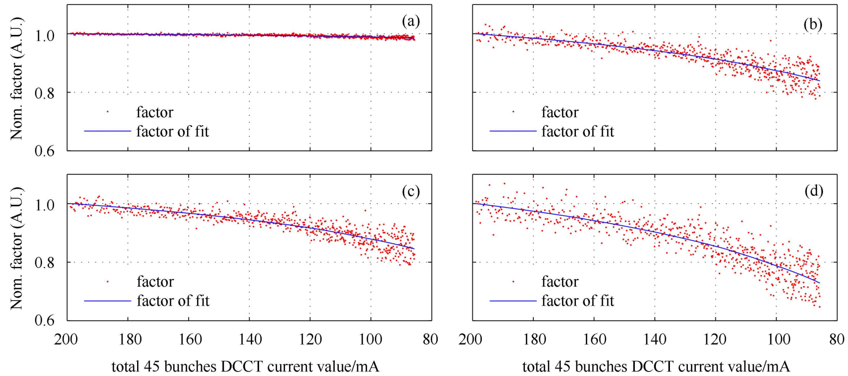

Fig. 7. Calibration factor changing with bunch current value. (a) strip-line and integral, change rate=1.4%; (b) button and integral, change rate=16.1%; (c) strip-line and peak, change rate=15.5%; (d) button and peak, change rate=27.1%.

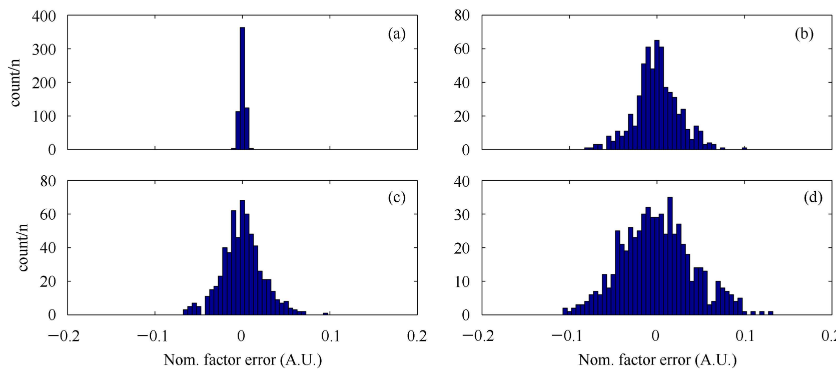

Fig. 8. Normalized calibration factor error distribution. (a) strip-line and integral, rms=0.003; (b) button and integral, rms=0.025; (c) strip-line and peak, rms=0.023; (d) button and peak, rms=0.041.

results are shown in Fig. 7. With the strip-line pickup and integral (Fig. 7(a)), the normalized calibration factor changes only by 1.4% when the bunch length changes by 19.3%, the measurement RMS is 0.003. The factor change rate is 16.1% with the button pickup and integral (Fig. 7(b)), 15.5% with the strip-line pickup and peak value, and 27.1% with the button pickup and peak value.

Figure 8 shows the related normalized calibration factor error distribution and its RMS.

4 Conclusion

The theoretical and experimental data analysis shows that using strip-line as signal pickup and processing the sum signal waveform by integral, the bunch length stretch effect on the calibration factor can be omitted. So, for the HLS-II bunch current measurement system, the strip-line pickup and integral method is finally selected to calculate the calibration factor and get the absolute bunch by bunch current value.

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